A STUDY OF CYBER-ATTACK RESILIENCE IN A DER-INTEGRATED SYNTHETIC GRID BASED ON INDUSTRY STANDARDS AND PRACTICES

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

The power transmission grid plays a pervasive role in modern society and its failure has a significant impact. In the past, the grid has been subjected to malicious attacks. With the increasing prevalence of distributed energy resources (DERs) and other renewable energy generation sources, there is a need to better understand the potential risks that arise due to the interdependencies and to develop mitigations. Hence, the objective of this work is to develop a methodology for modeling and analyzing DER threats, leveraging realistic electric grid models. This work develops a case study that models and evaluates situations of malicious DER failures and examines their impacts on steady state stability, voltage drop, and production and marginal costs related to analyzing the effects of DER failure.

In this study, we consider the next-generation Low Voltage Ride-Through requirements for DERs as established by (North American Electric Reliability Corporation) NERC. These requirements dictate plausible DER modeling standards for bulk system stability studies. Further, we analyze the standard practices prevailing in the power system industry and use these to measure how to mitigate DER security and reliability challenges, as well as how to reduce the vulnerability of the system to blackouts during instances of cyber-attacks on increasing DER integration.

Hence, this research provides a holistic study for the integration of DERs to the grid, analyzes the impact of cyber threat to DERs on the grid, and offers a simulation environment for further studies of DER interference to electric grid.

DEDICATION

"Gurustu diipavan maarga darsakah".

The teacher is like a lamp that lights up the path.

To my father, and mother for being my first teacher. To teachers for enlightening our path.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a committee consisting of Professor Davis, Professor Overbye, and Professor Rajendran of the Department of Electrical and Computer Engineering and Professor Goulart of the Department of Engineering Technology & Industrial Distribution.

The data analyzed for Chapter 3 was provided by Professor Overbye. The analyses depicted in Chapter 3 were conducted in part by Jessica L. Wert of the Department of Electrical and Computer Engineering and were published in 2021.

All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

P	REAL POWER
Q	REACTIVE POWER
S	COMPLEX POWER
V	BUS VOLTAGE MAGNITUDE
Θ	BUS VOLTAGE ANGLE
G	LINE CONDUCTANCE
IPH	SOLAR-INDUCED CURRENT
IR	IRRADIANCE
IPHO	SOLAR GENERATED CURRENT FOR THE IRRADIANCE
K	BOLTZMANN CONSTANT
B	LINE SUSCEPTANCE
DER	DISTRIBUTED ENERGY RESOURCES
PV	PHOTOVOLTAIC
WECC	WESTERN ELECTRICITY COORDINATING COUNCIL

MPPT	MAXIMUM POWER POINT TRACKING
SHINES	SUSTAINABLE AND HOLISTIC INTEGRATION OF ENERGY STORAGE AND SOLAR PV

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Motivation

With each new smart grid technology introduced into the power grid, the threat of cyber-based attacks that may impact power grid reliability and resilience increases. Attacks targeting the grid are also increasing and becoming more sophisticated. A major recent smart grid development has been the wide-spread increase of grid-connected Distributed Energy Resources (DERs). While DER technologies can offer tremendous benefits, the attack surfaces exposed and the potential impacts of integrating these technologies need to be more rigorously understood. Major cyber incidents can lead to large scale blackouts, equipment damage, and other major socioeconomic consequences on the grid. This fear came to realization for Ukraine on 23rd December 2015, when hackers used malicious code to temporarily take down three power substations on the Ukrainian national grid, causing hundreds of thousands of homes in the Ivano-Frankivsk region of the country to be left without electricity. This incident became an eye-opening lesson for many countries regarding the importance of cybersecurity in next generation power grids.

There is also ample evidence that many power system networks in US [1-3] and abroad [4] are the target of active cybersecurity reconnaissance and attacks. Therefore, many new research efforts are being directed toward cybersecure DER-integrated grids to achieve resilience in face of such highly advanced adversaries. This goal requires appropriate simulation of infrastructure comprising the DER integrated grid and the networks connecting it.

Penetration and Location

Between 1985 and 2020, USA's energy production from solar resources has increased 1,235,123% accounting for most sought-after renewable resource after wind in the period [5]. Due to its vast availability, the world has seen 586.19 GW absolute growth in solar related power generation since 1997[5]. This can be attributed to technological improvements, government subsidies, and material cost reduction.

After years of technological advancements in this field, solar photovoltaic (PV) has technically and commercially become mature technology as of current. Still, only 1.02% of total energy generation in USA and 1.10% in world comes from solar PV [5]. Some reports indicate annual growth in PV installation is 40% worldwide, which was made possible by almost one third price reduction of the technology in past 5 years. This trend is expected to continue in near future leading to delivery of 1081 GW by 2030.

Technology

Solar energy can be converted and used as heat, kinetic energy, electric energy, and chemical energy. PV systems generate electrical energy directly from the solar irradiation, where a PV cell contains layers of semiconductor material to convert the incident sunlight to electric field across it, leading to electricity flow. The cells are connected to form PV panels and arrays. The efficiency of conversion is an important parameter for solar arrays dictating their establishment in the power system industry. The Monocrystalline silicon solar cells have been around since 1950s and have shown promising improvement in conversion efficiency from 15% in 1950s and continuously increasing up to 28% 2010s [6].

The Shockley-Queisser limit, which limits the extent of efficiency of maximum efficiency for solar cell from a material, puts silicon at 30%. Recent solar technologies like Perovskites have been pushing these limits by combining six different materials into one multi-junctional cell with efficiency of 47%. In one of the most recent Perovskites solar cells (PSC) studies the efficiency of the PV array was boosted using capsaicin, the substance that causes chili peppers to taste hot [7].

This thesis therefore focuses on grid connectable Monocrystalline Module technology employed by leading solar manufacture SunPower. As the efficiency evolves with research in the field, the solar PV systems have potential to become significant. Hence, the subject matter covered in this thesis is expected to become increasingly relevant.

Interconnection Requirement

Interconnection requirements determine the performance of DERs under certain conditions. IEEE Std. 1547-2003[9] is the de-facto interconnection standard in the U.S. In its current version, it does not require voltage or frequency ride-through. On the contrary, it actually requires a mandatory trip of DERs for certain abnormal voltage or frequency conditions.

Ride-through is described by EPRI [1] as “Feature of DERs that allows them to stay connected to grid through a fault and then return automatically to its original current output.” Lack of ride-through can be a major issue for a grid with high DER penetration.

Several ride-through standards have been introduced with NERC Standard PRC-024-02, WECC VRT, FERC order 661-A, and IEEE Std. 1547-2003[24].

Table 1 provides clearing time for DERs for abnormal voltages based on IEEE Std 1547-2003. Table 2 deals with the clearing time for DERs in case of frequency outside of normal range. Clearing time is the time required by DERs to stop emerging the area. The size of DER also dictates the clearing time.

Table 1 IEEE Std. 1547-2003 voltage trip requirements [9]

Voltage range (% of base voltage)	Clearing Time (s)
V<50	0.16
50≤V<88	2.00
110<V<120	1.00
V≥120	0.16

Table 2 IEEE Std. 1547-2003 voltage trip requirements [9]

DR size	Frequency range (Hz)	Clearing Time (s)
<=30 kW	>60.5	0.16
	<59.3	0.16
>30kW	>60.5	0.16
	59.8 to 57.0	0.16 to 300
	<57.0	0.16

Research Objective and Approach

The objective of this thesis was to develop the required simulation infrastructure and methodology to analyze the stability issues and provide holistic study of impacts of malicious cyber-attack on power systems with a high penetration of DERs. Furthermore, the goal is for the outcomes of this thesis to be used to help propose an attack-resilient framework for critical infrastructure and provide a quantifiable resilience rubric for secure integration of DERs. Specially, the thesis aims to present and simulate the architecture involved with DER integration, the cybersecurity challenges introduced due to the integration, and steps required to mitigate the challenges and increase resilience to the infrastructure.

Hence, this work has developed a Simulink model of Solar PV [10]. This has been coupled with a transmission grid as well as a communication network to create a coupled infrastructure. This work described can open the gateway to different analyses and red team/blue team assessment of DER systems in real time in an emulation platform.

The case used to design this simulation is from a dataset called ***syn-austin-TDgrid-v03***, which is a highly detailed synthetic electric grid data set for combined transmission and distribution systems [11]. This case represents a synthetic grid version of the Travis County of central Texas with 140 substation and 448 feeders [11]. This case was selected, because this detailed T&D system facilitates analysis of coupled infrastructure as per the goal of this thesis.

In designing the simulation, the development included a Simulink model file with ***.slx*** extension which is block diagram model of 30KW of PV array based on a specific manufacturer design, SunPower SPR-305E-WHT-D. In attempt to model the case as realistic as possible, the model was designed to follow the rooftop solar generation capacity and geographical location data made available by Austin Shines Project and Pecan Street Inc. for Austin, Texas. The generation pattern of the DER in this case has been modelled according to the data of participating households in Austin Shines project [12].

To provide the cyber aspect to the system, a directional network was created, connecting all the DERs in the system through aggregators. All three files combined provide an infrastructure for studying voltage stability issues caused by cyber threat to DERs in the grid.

The work in this thesis uses PowerWorld™ to perform the modeling and analysis of the transmission system, OpenDSS for the location of substations and connection nodes available in provided distribution system data, and MATLAB and Simulink for the modelling of PV system. These software packages were then tied together through scripts of Python 3.

CHAPTER II

DERS

DERs in this work are assumed to refer to electric generation units located at the distribution level of power systems. Their generation capacity varies from 3kW to 50MW and can be installed as standalone or parallel to grid [13]. In addition to solar PV systems, a vast range of technologies like fuel cells, microturbines, etc., are also employed as DERs.

General Model of Photovoltaic Array

This section presents the method of modeling and analysis of photovoltaic array in the MATLAB environment. To model the exponential characteristic of a PV cell, three modeling systems could be implemented. The first option uses differential equations or highly complex algebraic equations that can be used to model the diode behavior of PV cells. The second possibility is to use models of physical components like diodes, capacitors etc. available in Simscape™. The third approach is to use SimElectronics advanced component library, containing Solar Cell block. This is essentially a solar current source, with dependence on solar irradiance and temperature dependence This thesis utilizes this approach for modeling the DER system.

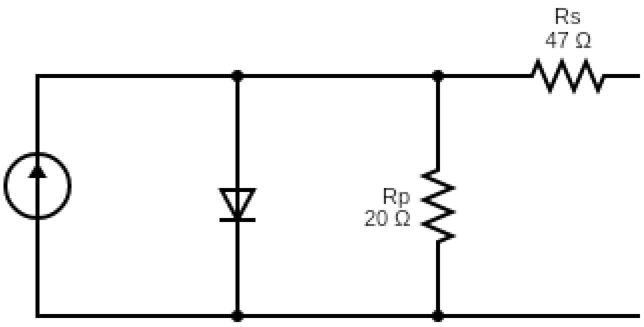


Figure 1 Electrical circuit of single diode model of PV cell

Solar Cell Parameters

The solar cell block displayed in Figure 1 is designed as parallel combination of diode and current source connected to series resistance R_s and a parallel resistance R_p. The output current source I is given by the following equation,

Equation 1

$$I = I_{ph} - I_s * \left(e^{\frac{V+I*R_S}{N*V_t}} - 1\right) - I_{s2} * \left(e^{\frac{V+I*R_S}{N2*t}} - 1\right) - (V + I * R_s)/R_p$$

where I_{ph} is solar-induced current, given as $I_{ph} = I_{ph0} *(I_r / I_{ro})$, where I_r is irradiance on the cell surface; I_{pho} is the solar generated current corresponding to irradiance I_{ro}; $V_t = kT / q$ is the thermal voltage, that depends on temperature T of the cell, k is the Boltzmann constant and q is the elementary charge of the electron; I_s is the saturation current of the D_1; I_{s2} is the saturation current of D_2; N_1 and N_2 is the quality factor for D_1 and D_2 respectively; V is the terminal voltage. This block model can be implemented in two ways. Firstly, using the above-mentioned equation, which requires 8 parameters. Secondly, by introducing the following assumptions to the equation: infinite impedance of the parallel resistor, and zero saturation current of D_2. This allows reduction of the required number of parameters to five. This model block can be optimized according to the equivalent circuit model parameters or by short circuit current and open circuit voltage.

Several solar cell parameters (Iph, I_{S1}, I_{S2}, R_S and Rp) are dependent on temperature TFIXED, the fixed circuit temperature. The relation between Iph and temperature of solar cell T is the following [10],

Equation 2

$$I_{ph}(t) = I_{ph} * (1 + TI_{ph1}.(T - Tmeas))$$

where TI_{ph1} is the first temperature coefficient for I_{ph}; T_{meas} is the parameter extraction temperature. This abstraction makes it easier for user as equations are modeled into the solar cell block of SimElectronics library. Block required two input parameters for output current calculation.

Modeling of PV Array

In this section, we discuss value determination of parameters required in equation $I_{ph}(t)$. These parameters are required to model a PV array. The material used in the array decides the values of diode ideality factor (a) and Energy gap (E_g). Since panels modeled in this thesis are based of SunPower's mono-crystalline silicon model, the values for diode ideality factor (a) and Energy gap (E_g) are 1.2 and 1.12 respectively. Table 3 gives the parameters of the PV array as specified by SunPower, and Figure 3 gives a high-level block diagram of the model for PV array in this thesis.

Table 3 Electrical parameters of the SunPower PV array modeled [14]

STC Power Rating	435W
PTC Power Rating	400.2W
Maximum System Voltage	1000V
Series Fuse Rating	20A
STC Power per unit of area	18.7W/ft2 (201.2W/m2)
Peak Efficiency	20.12%
Number of Cells	128
Imp	5.97A
Vmp	72.9V
Isc	6.43A
Voc	85.6V

Diode Current

To evaluate diode current at any temperature, reverse saturation current needs to be accounted for. Reverse saturation current at standard condition is given by [14]:

Equation 3

$$I_d = I_o \left[\exp\left(\frac{\frac{V + IR_s}{NS}}{aNVth} \right) - 1 \right]$$

At different temperatures, the reverse saturation current is calculated using

Equation 4

$$I_o = I_{o_n} (\frac{T}{T_{ref}})^3 exp \left[qE_g ((\frac{1}{T} - \frac{I}{T_{ref}})/K_a \right]$$

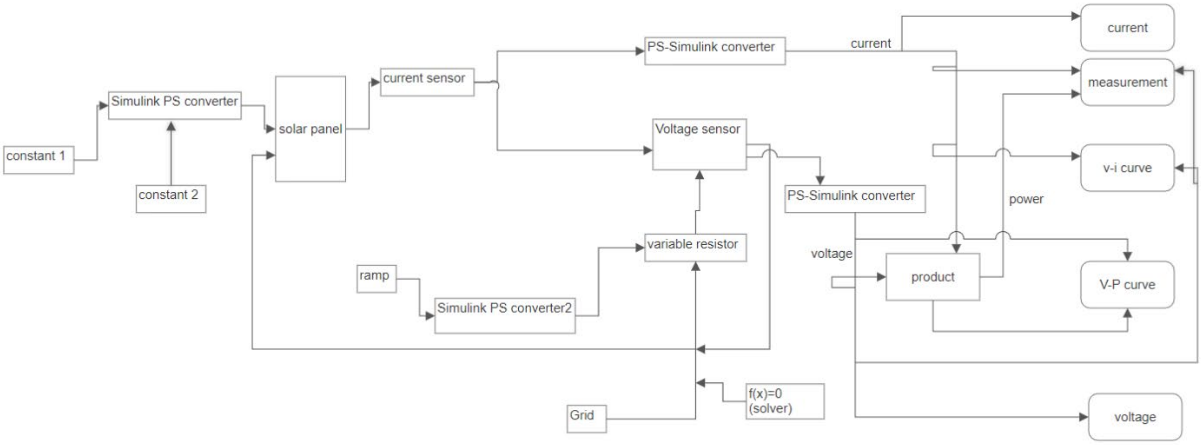


Figure 2 Block diagram of the model for photovoltaic array designed for simulation

MPPT in Photovoltaic system

The semiconductors in photovoltaic modules have a point called MPP (maximum power point) that occurs in the knee of the I-V curve where the generated power is at the maximum. The maximum power point tracking (MPPT) algorithms employed to search for the MPP usually measure and compare the power output from the module before and after changes of duty cycle [15].

To address the non-linear behavior and weather dependencies of PV module, a MPP tracker is introduced into the model. It facilitates m0061imum power delivery and increased efficiency by altering the duty cycle values for Insulated-gate bipolar transistor (IGBT). At maximum power point [14]:

Equation 5

$$\frac{dI}{dV} + \frac{I}{V} = 0$$

The module is operating at MPPT if the sum of (dI)/dV and I/V is zero. Otherwise, the PI controller/regulator tries to minimize this sum.

Boost Converter

Figure 3 shows the DC-DC boost converter used in the simulation model to regulate and boost the output voltage of the PV module. It also implements MPPT for the module. The output can be given by $Vo = Vin/\ (1 - D)$.

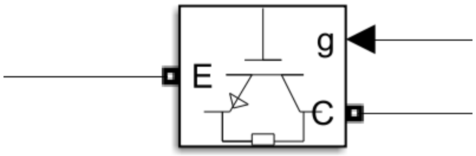


Figure 3 Buck Boost converter

DC-AC converter

Figure 4 shows the Simulink block used for DC-AC converter in this simulation. It is Three-phase three level voltage source converter with capacitors from boost converter acting as N for the inverter. The inverter control loop generates the gate signal that controls the IGBT on and off period.

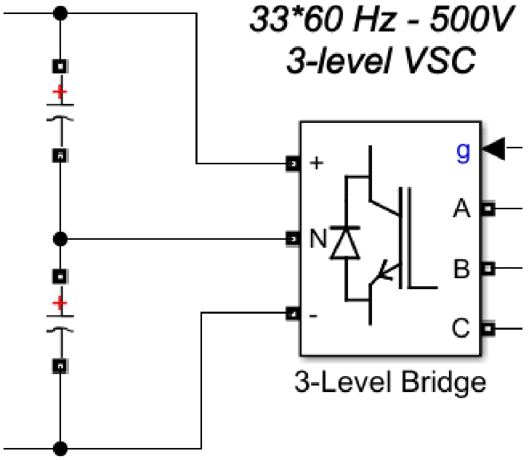


Figure 4 DC-AC converter

Extension of Model

In the simulation model (Figure 2), the PV module is connected to a variable resistor with input ramp. The resistance is linearly varied until it gets up to 30 steps. This PV module has 8 rows of PV cells connected in series or parallel, formed by 24 cells of SimElectronics® library (Figure 5). This structure is extended in this thesis using the block diagrams discussed in this chapter to create the grid configurable model for the solar PV array [14].

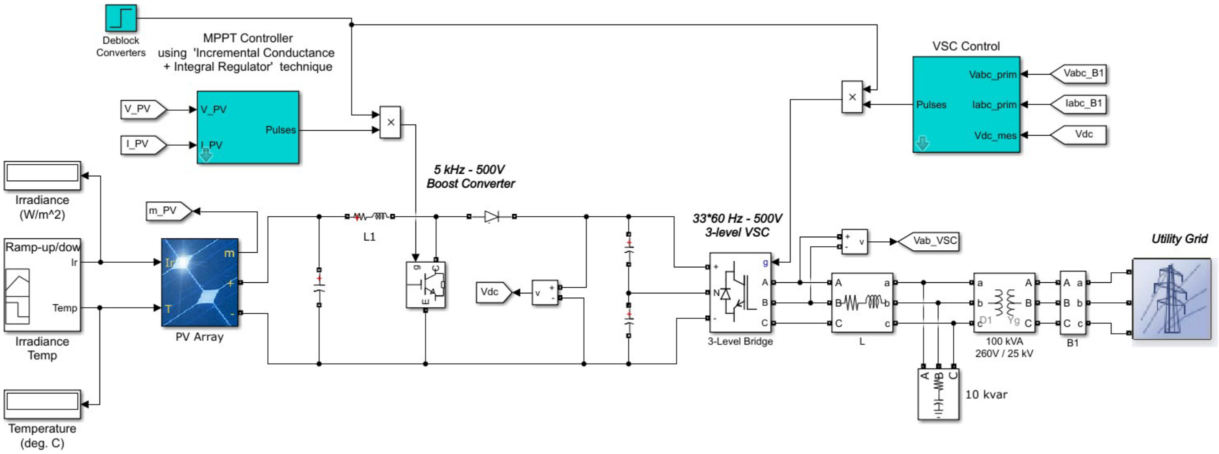


Figure 5 Model of single PV array connected to grid

CHAPTER III

GRID DATA

The grid data used in this thesis is based on research on synthetic grids. Synthetic grids are realistic and fictional power network models. They include detailed representation of generators, loads, transmission lines, and transformers [16]. The synthetic grid is based on geographically sited, publicly available data and statistics about the physical grid. This allows co-simulation and coupled infrastructure studies.

Test Case

In the thesis, we have utilized the highly detailed Synthetic Electric Grid Data Set for combined transmission and distribution systems [11] of Travis County, TX as the test case to demonstrate the coupling of power and DER networks. It includes the city of Austin and surrounding areas in central Texas. This data set serves 307,236 customers loads. The total system peak is 3,254 MW. This synthetic grid has total of 140 substations in the system, with voltages of 69 kV and 230 kV. These substations include 448 feeders, and 132,406 distributed transformers [11]. The average consumers on distribution level per transformer is 5.3; and the capacity of the transformer ranges 10-1500 kVA.

The diversity in the models is ensured by: 1) the different circuits and characteristics based of consumer’s location in rural or urban locality. Particularly, circuits have different network length and reliability. 2) Different nominal voltage levels 3) usage of voltage regulators and/or capacitor banks and other voltage regulation methods used. While the load is realistically provided in the data set. The geographical footprint has been altered to ensure confidentiality of critical energy infrastructure information. This dataset still provides the users with realistic test case for studies. This test case is publicly available for download at [17].

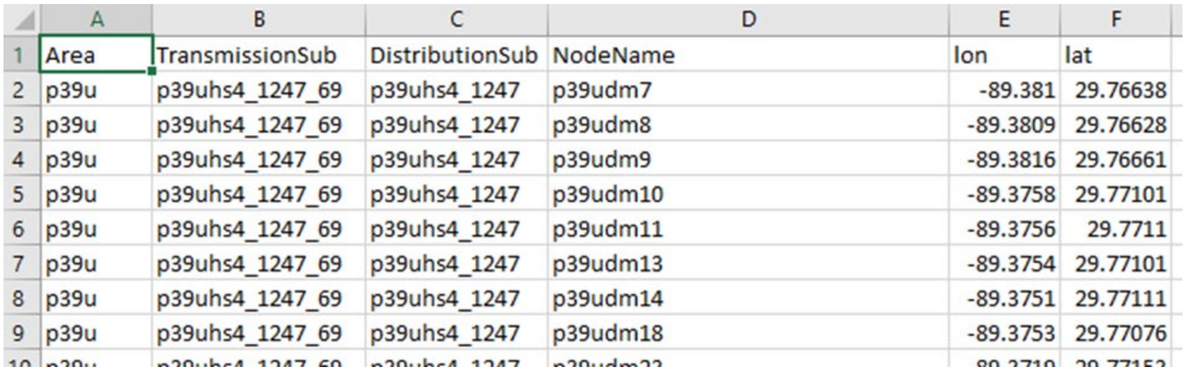
Table 4 The key statistics of the synthetic system, Travis160

Customer loads	307,236
Generator units	39
Feeders	448
69 kV transmission lines	229
230 kV transmission lines	34
Transmission buses	160
Distribution electric nodes	1,654,691

Substation Service Area

To map the DER generation from distribution node to the transmission-level substation. A technique of using Voronoi polygon to establish Substation service areas (service territory of each transmission substation) is used in the simulation. This leverages the geographical data of DERs, distribution node, and the transmission substation.

The procedure is as follows: 1) Select a transmission-level substation, 2) Identify corresponding distribution node, 3) Obtain geographic coordinates of the nodes, 4) Use Voronoi polygons to specify the reach of node, 5) Combine the polygons to denote the selected transmission-level substation's service area, 6) Repeat steps 1 to 5 [18]. This data generated is used to map the DERs to transmission node in synthetic grid. The parsed list of the transmission substation to corresponding Distribution node is presented in figure 6.



	A	B	C	D	E	F
1	Area	TransmissionSub	DistributionSub	NodeName	lon	lat
2	p39u	p39uhs4_1247_69	p39uhs4_1247	p39udm7	-89.381	29.76638
3	p39u	p39uhs4_1247_69	p39uhs4_1247	p39udm8	-89.3809	29.76628
4	p39u	p39uhs4_1247_69	p39uhs4_1247	p39udm9	-89.3816	29.76661
5	p39u	p39uhs4_1247_69	p39uhs4_1247	p39udm10	-89.3758	29.77101
6	p39u	p39uhs4_1247_69	p39uhs4_1247	p39udm11	-89.3756	29.7711
7	p39u	p39uhs4_1247_69	p39uhs4_1247	p39udm13	-89.3754	29.77101
8	p39u	p39uhs4_1247_69	p39uhs4_1247	p39udm14	-89.3751	29.77111
9	p39u	p39uhs4_1247_69	p39uhs4_1247	p39udm18	-89.3753	29.77076

Figure 6 Connection of the transmission vs the distribution node based on Voronoi polygons method

CHAPTER IV

COMMUNICATION NETWORK INDUSTRY STANDARDS

This chapter emphasizes the communication challenges and practices prevailing in power industry with respect to distribution systems and DERs. Since information on real utility communication is confidential under CEII (Critical Electric Infrastructure Information), this chapter reviews and presents consolidated information available in different reports by federal agencies like North American Electric Reliability Corporation (NERC) and Independent System Operators (ISO) regarding DER communication infrastructure. These challenges are generally rooted in the fact that the communication architecture is much more fluid than the physical architecture and is evolving continuously, making it hard to secure. The challenges and standards proposed by agencies are mentioned in detail later in this chapter. The primitive communication graph used in this thesis aims to provide a high-level framework for students and researchers to emulate and generate a realistic synthetic communication network in detailed resolution for future scope of this study.

Networks in Industry

This thesis considers the communication network from the device level to the utility control center. As a classification of the type of communication networks present in smart grids, the overall smart grid communications layer consists of three types of networks as shown Figure 7.

1) Wide Area Networks (WAN) is between the electric utility and substations and operates as a network for medium voltage and beyond. WAN usually is high bandwidth that manages long-distance data transmission.
2) Field Area Networks (FAN), Neighborhood Area Networks (NAN), and Advanced Metering Infrastructure (AMI) manages distribution areas. It connects the WAN to buildings.
3) Home Area Networks (HAN), Building Area Networks (BAN), and Industrial Area Networks (IAN) offer communication between Smart meters and other appliances.

These three layers employ several communication link methods and degree types for packet flow. For Inter-Substation Networks the degree types are 33.1% Microwave, 15.4% PLC, 22.8% fiber, 25.2% Leased and 3.5% low-capacity radio [27]. Other factors that influence modeling of the communication network are average degree load and routing path etc.

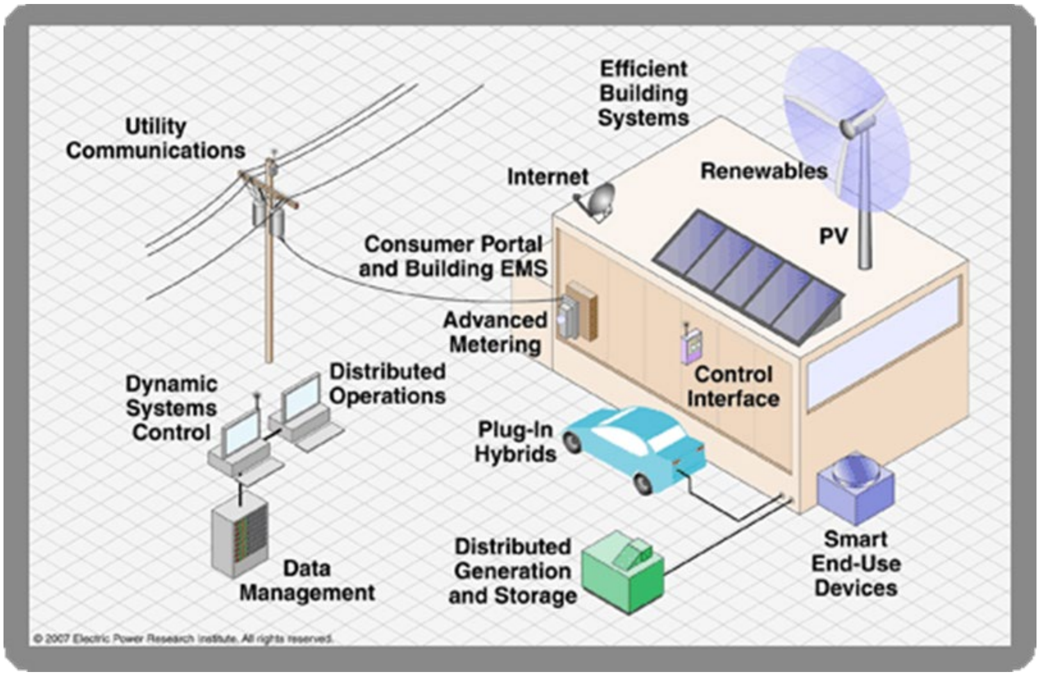


Figure 7 Three levels of communication involved with DER connection to utility Reprinted from [© 2016 IEEE]

Challenges

With the communication network being complex and decentralized, it already poses a huge challenge to make it secure for critical power system infrastructures. Detailed modeling of the communication network in a test bed can help researchers identify and address associated security challenges [30]. However, when DERs are introduced, they pose new set of resilience challenges to the network grid. A few of those are 1) Security responsibilities in a “Multiparty Grid” 2) Device authentication 3) Protection of data in transit 4) Third party cloud-based services for DERs 5) Advanced metering infrastructure components 5) Meter data management systems 6) Distributed energy resource management system (DERMS) 7) Uncertain impact from disruption of DERs [28]

Industry Requirements for Communication Networks

For the smart grid applications, the standardized communication requirements are as [19, 20]:

1) Latency requirements: Different components require different level of latency in their communication, such as real-time state estimation needs very low latency.
2) Data rate requirements by different component requires standardization of speed of data transfer.
3) Reliability requirements: To ensure reliable critical infrastructure a reliable communication network is essential.
4) Security requirements: confidentiality, integrity, availability, authenticity, and non-repudiation.

To study the power system on whole, combining power and communication network simulation to study volatility of smart power grids [21] has become a preferred approach being taken in recent years.

CPUC Standards for DERs

The California Public Utilities Commission (CPUC) regulates the largest rollout of DERs in North America in the California ISO balancing area. It also sets the technical and commercial standards for DER interconnection and operation according to its Rule 21 [23]. Rule 21 primarily follows the IEEE 1547 parallel operation DER interconnection standard, where generation is operating in parallel (synchronously connected) with the system rather than in an islanded or isolated mode. The CPUC report not only covers the new standards for DER systems but also notes how utilities will be able to monitor and control these systems and their functions. Most notably:

> *"DER systems can respond to commands to override or modify their autonomous actions by utilities and/or retail energy providers. In some cases, DER systems, just like bulk power generation, may be directly monitored and controlled by utilities in real-time. In other cases, these ICT [Information and Communications Technology] capabilities may issue emergency commands or may support normally autonomous operations by updating software settings, providing demand response pricing signals, establishing schedules for energy and ancillary services, adjusting the curves for active and reactive power, and other types of utility-DER interactions [24]."*

Not only the autonomous functionalities, California ISO is also planning to implement following advanced communication requirements to ensure standardization and uniformity among all third party DERs in the system [23]:

1) Capability for adding communications modules for different media interfaces.
2) Use the TCP/IP internet protocols.
3) Use IEC 61850 for the information model.

4) Support the mapping of the IEC 61850 to other communications protocols.

5) Ensure cybersecurity at different communication layers.

6) Ensure cybersecurity for user and device authentication.

These requirements aim to provide resilience to the utility's distribution system and address the challenges mentioned earlier in this chapter.

CHAPTER V

STUDY AND RESULT

This chapter provides the insight into the steps employed for the study. First, it describes parameter correction and simulation of DERs based on data from Austin SHINES. The second step involves the mapping of DER network to transmission system. The third step is to generate the communication network for the DER network in system. Finally, studies are done executing cyber threat scenarios on the DERs to study the impact on grid. The system architecture is displayed in Figure 8.

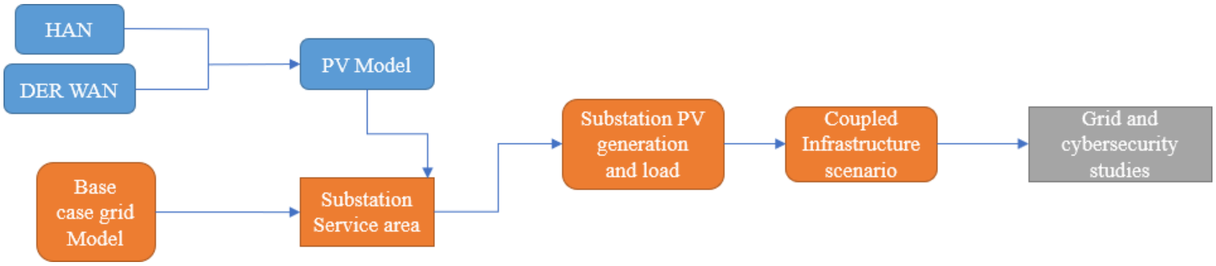


Figure 8 System architecture diagram for the study

DER Simulation

The city of Austin gets fixed tilt sunlight hours (the number of hours of sunlight a fixed tilted non-tracking solar panel receives) of 5.3 hours per day and averages 4.0-4.5kWh/m2/day of solar Irradiance [25]. Hence for the simulation, solar irradiance was assumed as displayed in Figure 9. The aggregate Irradiance for the day comes out to be 4.3kWh/m2 to make it as realistic as possible.

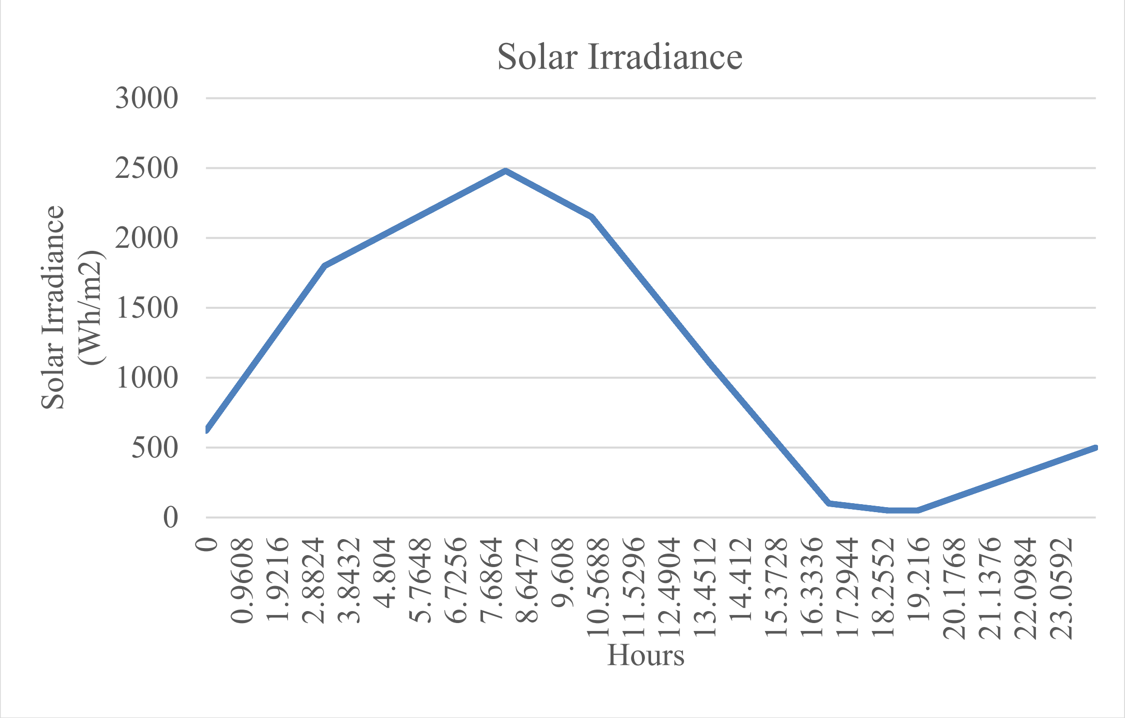


Figure 9 Solar Irradiance used for simulation of DER

the other constant required for simulation is hourly temperature. And the temperature used in the study is between 77 °F to 90 °F to simulate an average in the location. Figure 10 displays the fluctuation of temperature used in the simulation. The data set generated here is of 30000-time steps, spread over 24 hours.

Mapping of DER Generation to Transmission Grid

The DER nodes are mapped to the transmission system according to the substation service areas established in Chapter 3. If the DER node falls within the geographic footprint of a substation, it indicates that its most proximate distribution point of interconnection would aggregate to the specified transmission-level substation and thus, its load is best represented as an addition to the identified transmission-level substation.

The DERs are mapped as generation, where the dataset ensures that generation is variable on a schedule.

Figure 11 displays the variable generation of PV based on parameters provided to the model. The maximum generation is 46.8KW which occurs during afternoon duration of the simulation. For 30% penetration, a total of 182.52MW of generation is scheduled through PV arrays. Assuming each DER cluster consists of 100 rooftop PV arrays. Thus, the total open generation available for the case is 3517.78MW through traditional sources and 182.52MW from attached DERs, making them a critical generation unit for the system

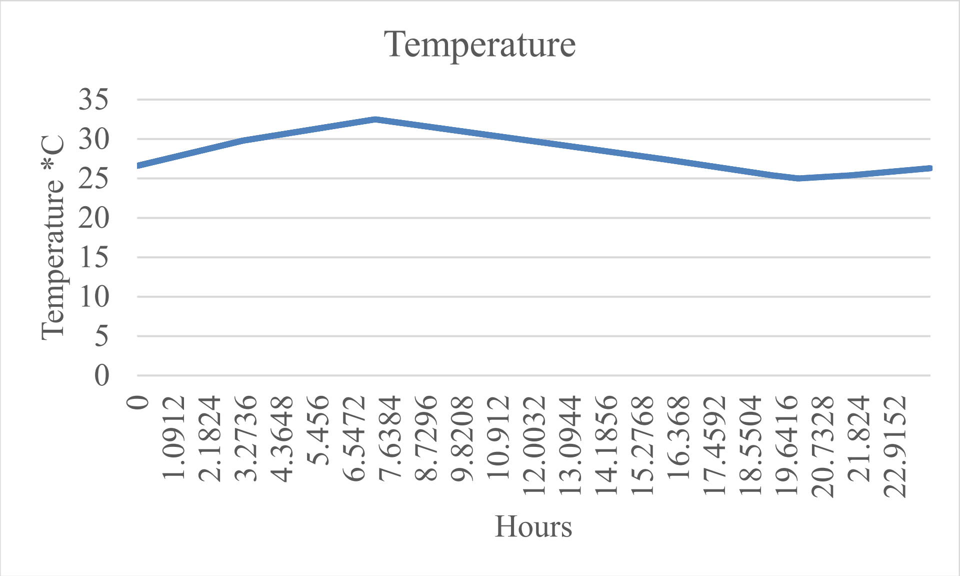


Figure 10 Temperature used for simulation of DER

The schedules and schedule subscription feature available in PowerWorld are used here to update the load and generation of mapped DERs to the system as shown figure 12.

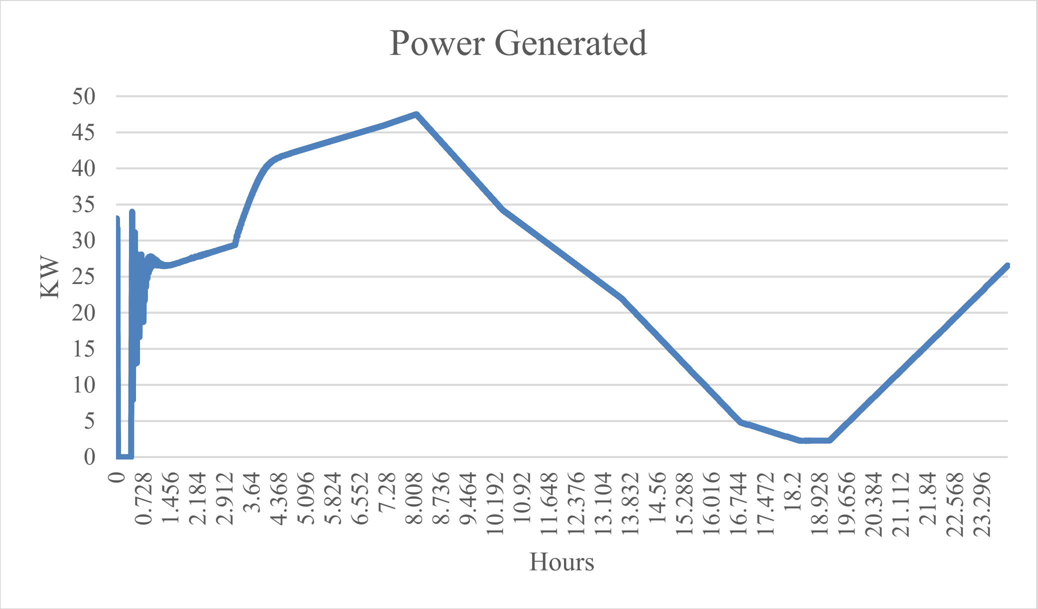


Figure 11 Pmean generated by single PV array during 24-hour simulation

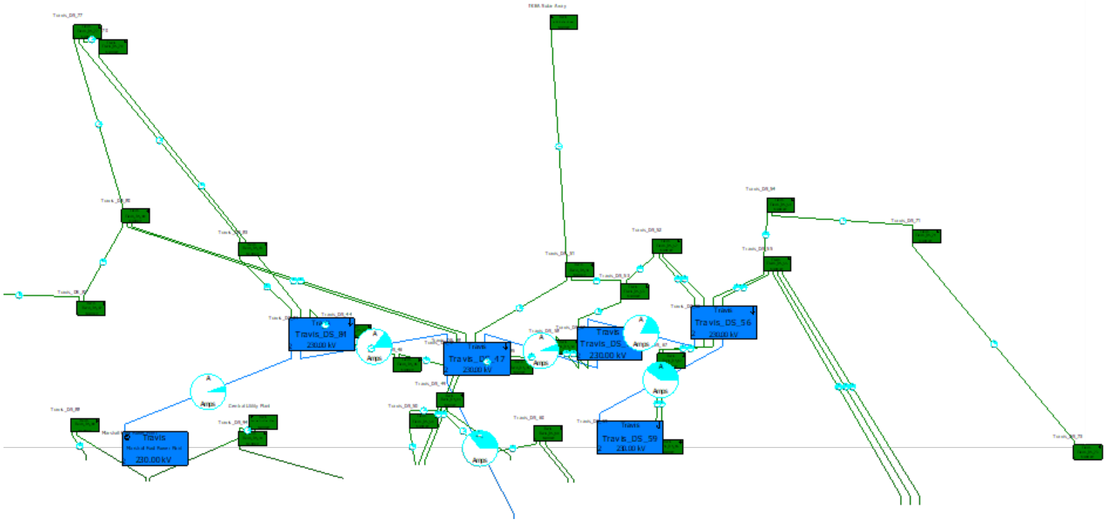


Figure 12 The transmission system with generation and load updated from DER

Network for the DERs

To simulate a real-time network associated with DERs in the Austin power system, a primitive network graph methodology using vertices and edges, which represents a cyber-physical network of the county is used. The vertices denote network nodes or physical devices, and the edges denote a communication link between the nodes. Vertices and edges have attributes. A vertex that is a DER with router connection could have attributes such as the IP address, configuration, and generation information. Attributes of an edge could include, for instance, the protocol used in that link, such as DNP3.

The NetworkX Model employed here has also parameters specifying the connection nodes, data, and location of particular DER. This model provides PV generation data at geographically represented nodes each hour of the day. This information provides essential details for the coupled infrastructure: the connectivity to entire communication network. Hence, it allows the study of execution and defense of assumed threats to the system.

Due to limitation of NetworkX to execute any threat commands to power system simulation software, the connection between two software is an assumption in this study. The network graph generated by NetworkX is visualized in Figure 13.

The graph model has each of 39 DER cluster as a node with attribute of maximum MW generated among other data. They are connected in a directed graph fashion towards their respective aggregators. The DiGraph class provides additional methods and properties specific to directed edges. The aggregators are connected in bidirectional fashion and have ability to make multiple edges between two aggregators using MultiDiGraph class available in NetworX library [25].

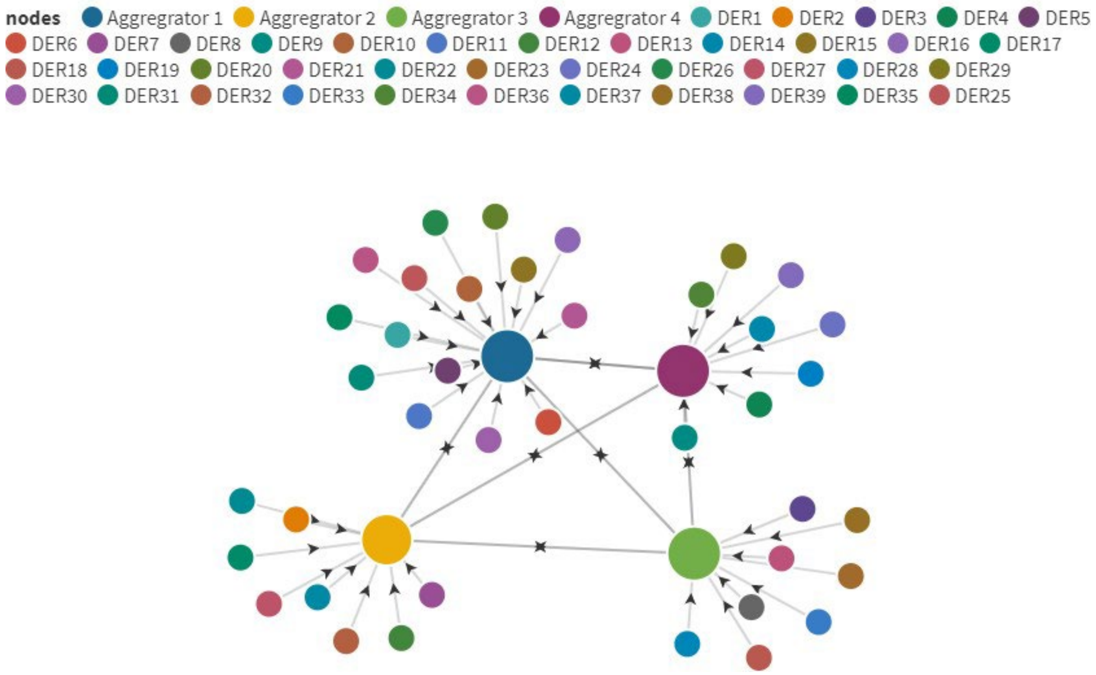


Figure 13 Visualization of generated network graph for mapping of DER in the communication network

A separate script is employed to simulate the network threat to aggregators in an ordered fashion. In the first step, two aggregators are taken out to simulate 25% blackout of DERs in the area. Then, all four aggregators are taken out of service to simulate 100% DER blackout in the area. The summary of the steps employed in this setup is displayed in figure 14.

Grid Impact Analysis

A key question to address while considering increasing PV in grid how the grid changes along with it. The simulation environment allows the study of this impact on grid due to increased PV. Results of the simulation as present below, proved that while 30% PV integration did not cause any violations, the most noticeable effects were change in energy cost, generation cost ($/hr.) and marginal cost of production was decreased as displayed in figure 15.

System loading studies were also performed to indicate any vulnerable points in case of extreme load scenarios. During the 24-hour period of the simulation, no bus voltage limits are violated.

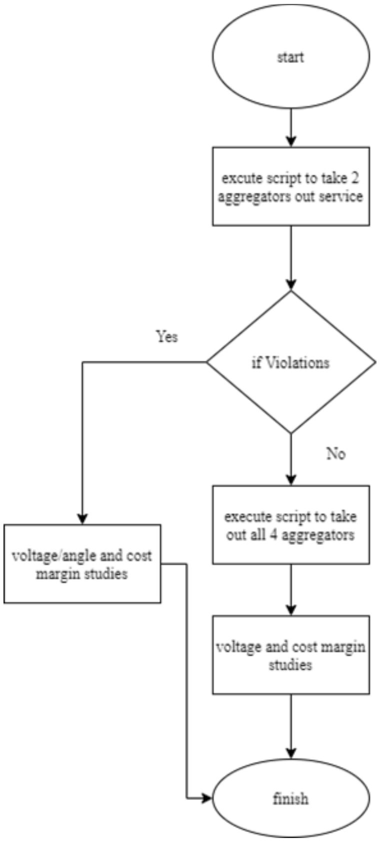


Figure 14 Steps involved in the study of voltage loss due to loss of DERs

Figure 16 shows the drop in bus voltage angle due to 25% drop in generation by DERs in the system which accounts for 45.63MW only in a system of 3517.78MW.

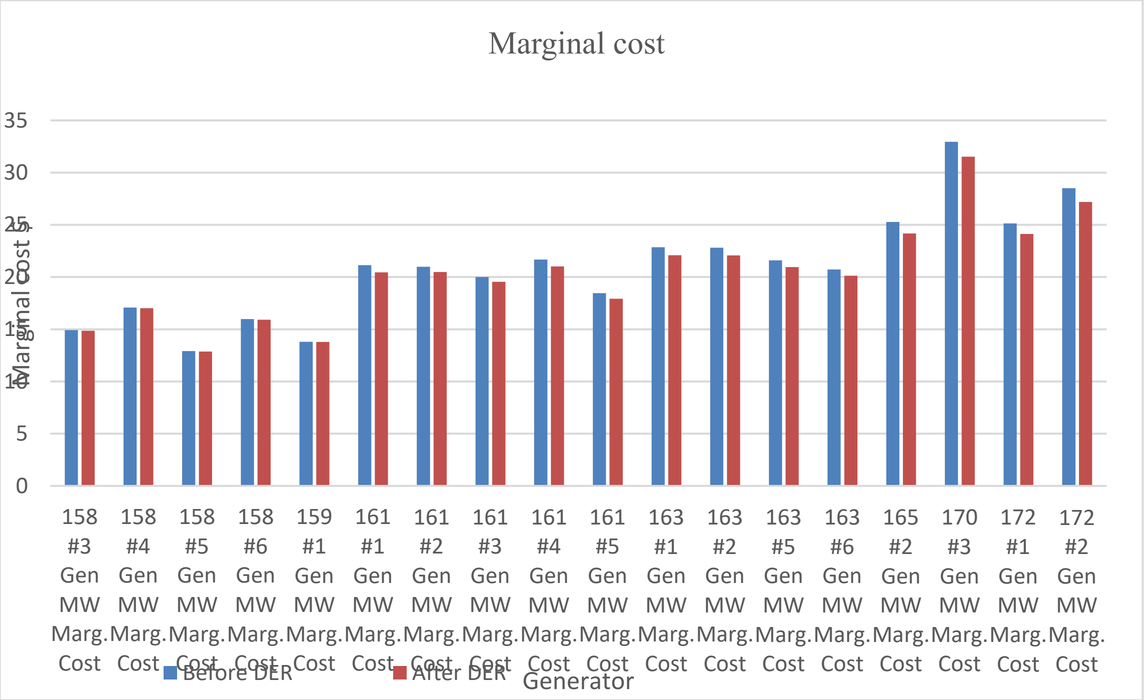


Figure 15 Decrease in Marginal cost after introduction of DERs

Hence there is nominal change in Marginal cost of generation for most of the traditional generators as displayed in figure 17.

While in case of 100% DER blackouts, there is significant voltage drop (p.u) with most of the buses attached to DERs generation units. The maximum is an almost 40% drop in voltage for bus 156.

Similarly, marginal cost analysis shows significant increase in cost/MW during the event of threat. Figure 18 displays the changes in marginal cost during and after the event for the generators mostly effected by the event, while Figure 19 provides insight into the per unit voltage drop experienced at each bus effected during the event

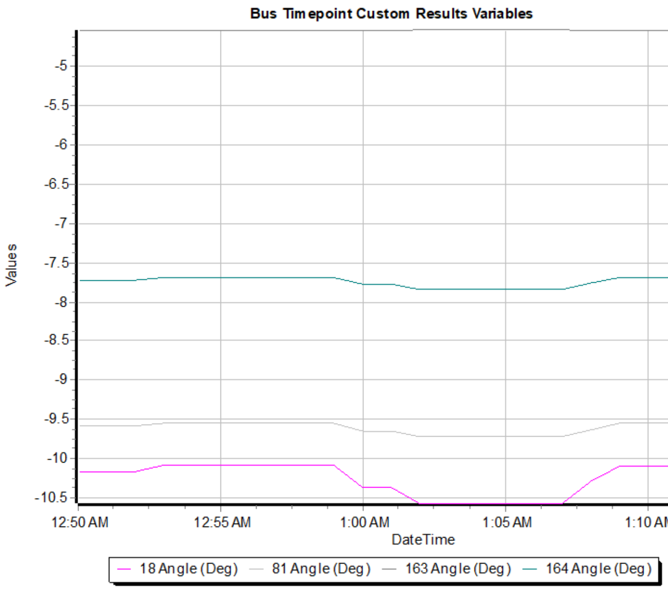


Figure 16 Voltage/angle during 25% DER blackout threat

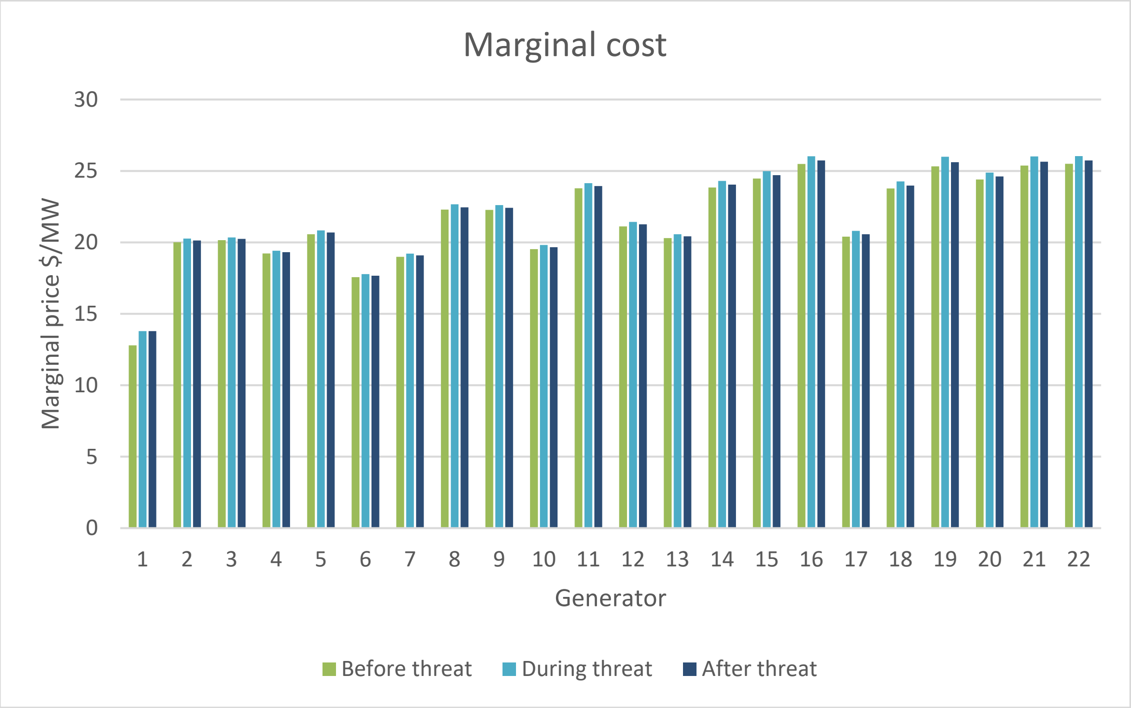


Figure 17 Marginal cost before, during and after 25% threat

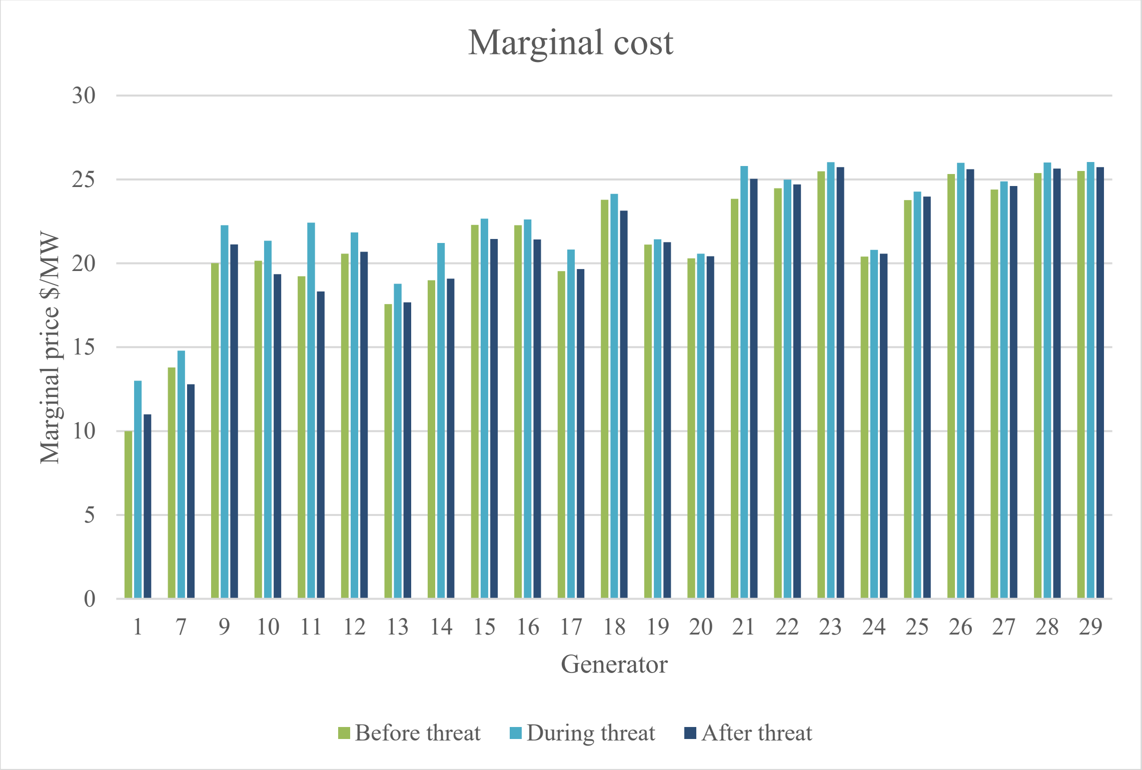


Figure 18 Marginal cost for generators before, during and after 100% threat event

Along with above mentioned results and analysis methods, there were different analyses performed on setup at different threat levels. And the data presented above is validated through the data provided by ERCOT in their study of renewables in the system [26]. The ERCOT DERAU1 model's ride through response abnormal voltage was modeled according to IEEE 1547-2018. ERCOT's study even through only considered 5% and

10% penetration for net load of 3150MW.

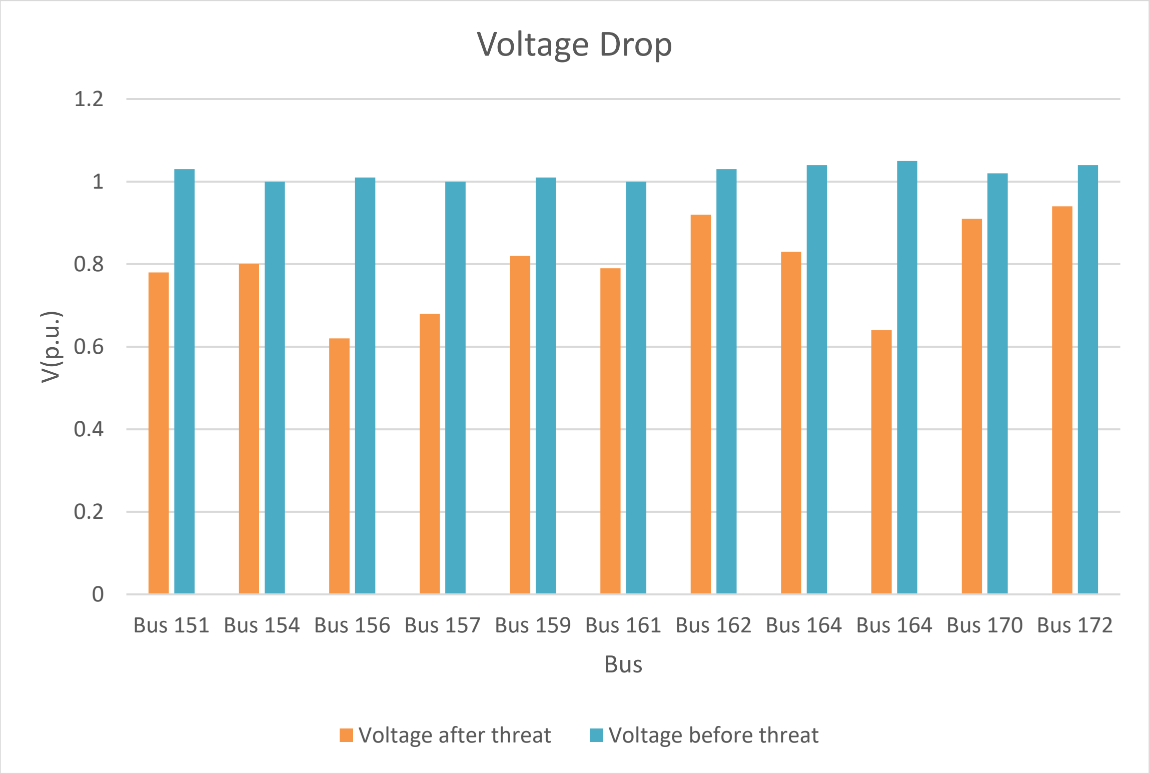


Figure 19 Bus voltage drop before, after 100% threat event.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

Conclusion

This thesis introduced the interconnection of DERs to the power system, coupled with cyber infrastructure. The introduced DERs are then disconnected from the communication network due to a assumed cyber threat. This thesis also provides insight into design and deployment of photovoltaic arrays to the grid. It also discusses the most updated interconnection standards i.e IEEE 1547-2018, essential communication requirements for DERs like IEC 61850, standardization of cybersecurity for user and device authentication etc, being employed in industry across USA.

The second part of thesis provide the vulnerability analysis of the various parameters involved the system and highlights the vulnerability of system to operational impacts introduced through loss of service of DERs in the system. This grid impact analysis is validated by ERCOT study [26] which also concluded that DER can negatively impact the net load serving capability of the grid (even at relatively low penetration levels) and needs to be explicitly modeled to tackle the potential reliability issues. The study also validates the interconnection discussion on ride through voltage, clearing time and other benefits of dynamic voltage support introduced by IEEE 1547-2003.

In summary, the contribution of this thesis to existing literature is to:

1) Extend and fine-tune the design of photovoltaic array models for interconnection to existing grid systems

2) Develop infrastructure of DER interconnected to transmission system using Voronoi polygon technique.

3) Provide insight into grid impacts such as voltage drop caused due to loss of DER in the system. By presenting a modeling pipeline from the PV modules to the cyber and physical transmission and distribution power system infrastructure, this thesis provides an approach for the realistic study the vulnerability of system towards newly introduced DERs.

4) Provide insight into the updated communication standards to monitor and control the DERs in real time and requirements for emergency command, threat assessment and utility-DER interactions employed in industry that bolster resilience in the interconnection.

Potential for Future Work

The potential for future work includes the incorporation of more system parameters such as forecasting of generation based on weather pattern being introduced. The DER model can be redesigned to inculcate more secure control system to increase resilience explicitly. Also, it would be useful to perform the design and study in OpenDSS™ to study the effect and resilience on distribution systems to such threats. The involved cyber-infrastructure has potential to be redesigned to have industry level enhanced security. Such potential redesigns can then be emulated in cyber-physical testbeds to provide more realistic studies for red team assessment and defense designs. The present study focuses on a fundamental communication and DER model, where usage of variations of these models and/or more detailed models that can be developed can provide utilities with additional results and accurate insights that help them deploy DERs in a more secure and reliable way.

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